Influence of Temperature on the Performance of a Spin-Torque Microwave Detector

Oleksandr V. Prokopenko[1], *Member, IEEE*, Elena Bankowski[2], Thomas Meitzler[2], *Member, IEEE*, Vasil S. Tiberkevich[3], *Member, IEEE*, and Andrei N. Slavin[3], *Fellow, IEEE*

[1]Taras Shevchenko National University of Kyiv, Kyiv 01601, Ukraine
[2]U.S. Army TARDEC, Warren, MI 48397 USA
[3]Oakland University, Rochester, MI 48309 USA

We analyzed the influence of temperature on the main characteristics of a passive spin-torque microwave detector (STMD): volt-watt sensitivity, signal-to-noise ratio, and minimum detectable microwave power. We reveal that these parameters do not always improve with the decrease of temperature. The developed formalism can be used for the optimization of the practical parameters of a STMD in a wide range of temperatures.

***Index Terms*—Microwave detector, noise properties, spin-transfer torque, temperature.**

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I. Introduction

THE spin-transfer-torque (STT) effect in magnetic multilayers was theoretically predicted in [1], [2] and experimentally observed in [3]–[13]. It provides a new method of manipulation of the magnetization direction in nano-magnetic systems [14] and can be used for magnetization switching [3], [4] and generation of microwave oscillations under the action of a DC electric current [5]–[10], [14]. Another manifestation of STT, so-called spin torque diode effect [11]–[13], can be used for the development of practical microwave detectors (spin-torque microwave detectors (STMD)) and for quantitative experimental determination of the STT parameters [15], [16].

The spin torque diode effect is a quadratic rectification effect of the input microwave current $I_{\rm RF}(t)$ in a magnetoresistive junction, which is commonly observed in the traditional regime of operation of a STMD, when the frequency f_s of the current $I_{\rm RF}(t) = I_{\rm RF}\cos(2\pi f_s t)$ is close to the ferromagnetic resonance frequency f_0 of the magnetic tunnel junction (MTJ). In this case the induced resonance oscillations of the junction resistance $R(t)$ can mix with the oscillations of the input microwave current $I_{\rm RF}(t)$ and produce a sufficiently large output DC voltage $U_{\rm DC} = \langle I_{\rm RF}(t)R(t)\rangle$ across the junction (here $\langle\ldots\rangle$ denotes averaging over the period of oscillations $1/f_s$).

It has been shown in [11]–[13] that in this regime of operation, a STMD performs as a resonance-type quadratic detector of microwave radiation generating a DC voltage $U_{\rm DC}$ proportional to the acting microwave power $P_{\rm RF}$: $U_{\rm DC} = \varepsilon P_{\rm RF}$ ($P_{\rm RF} \sim I_{\rm RF}^2$). The detector sensitivity ε has a maximum value $\varepsilon = \varepsilon_{\rm res}$ [17] when the frequency of the external microwave signal f_s is close to the eigen-frequency f_0 of the MTJ nanopillar, $f_s = f_0$.

Recent experimental results [12], [13], [18], [19] have demonstrated that the volt-watt sensitivity $\varepsilon = U_{\rm DC}/P_{\rm RF}$ of a STMD based on the spin-torque diode effect can exceed that of passive semiconductor Schottky-diode microwave detectors. This makes STMDs very interesting for practical applications in microwave electronics.

The operation and the performance of all types of microwave detectors are limited by noise (in particular, by the low-frequency Johnson-Nyquist noise in the case of unbiased Schottky diodes [20]), and, therefore, depend on the temperature. In the case of magnetic STMDs the temperature dependence of detector's characteristics may be non-trivial, since many STMD parameters besides the noise level (e.g., saturation magntetization and spin-polarization efficiency) also change with the temperature.

In this work we analyze the influence of temperature T on the performance of a passive STMD, namely, we studied the temperature dependences of STMD sensitivity $\varepsilon_{\rm res}$ [17], signal-to-noise ratio SNR, and minimum detectable microwave power $P_{\rm min}[50\ \Omega]$ (for a detector connected to a standard 50 Ω transmission line) [21]. We believe that the developed formalism can be used for the optimization of the practical parameters of an STMD in a wide range of temperatures.

II. Theoretical Model

In this section we present a theoretical analysis of the performance of a passive STMD (no DC bias current) using the STMD model developed in [16], [21].

We consider a "planar" STMD based on a isotropic circular nanopillar of the radius r, in which both the free magnetic layer (FL) and the pinned magnetic layer (PL) are magnetized in-plane. In this case, the MTJ eigen-frequency is $f_0 = (\gamma/2\pi)\sqrt{B_0(B_0+\mu_0 M_s)}$ and the damping rate has the form $\Gamma = \alpha\gamma(B_0 + \mu_0 M_s/2)$, where $\gamma \approx 2\pi\cdot 28\ {\rm GHz/T}$ is the modulus of the gyromagnetic ratio, M_s is the saturation magnetization of the FL of MTJ, α is the Gilbert damping constant, μ_0 is the vacuum permeability and B_0 is the in-plane bias DC magnetic field.

For simplicity we use the macrospin approximation for the FL of a STMD and also assume that the FL is isotropic over the entire temperature range. If this is not the case a more rigorous analysis should be performed [14]. Despite the obvious

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14. ABSTRACT
We analyzed the influence of temperature on the main characteristics of a passive spin-torque microwave detector (STMD): volt-watt sensitivity, signal-to-noise ratio, and minimum detectable microwave power. We reveal that these parameters do not always improve with the decrease of temperature. The developed formalism can be used for the optimization of the practical parameters of a STMD in a wide range of temperatures.

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limitations of this model, we believe that it is qualitatively correct for isotropic magnetic materials (e.g., permalloy), at least for temperature range from 10 K to 300 K. If the materials with significant crystalline and strain-induced magnetic anisotropies (e.g., Co) are used for the MTJ free layer (see e.g., [12]) a more sophisticated model for the magnetic state of the MTJ free layer at low temperatures might be needed.

We used the analytical theory of noise properties of a STMD developed in [21] and the expression for the resonance detector's sensitivity $\varepsilon_{\rm res}$ from [17]. We took into account two sources of thermal noise: low-frequency Johnson-Nyquist noise, which is characterized by a noise power $P_{\rm JN}$, and the magnetic noise with noise power $P_{\rm MN}$ (see [21] for details).

We assumed that the spin-polarization P of the bias current in the STMD depends on the temperature T as

$$P(T) = P(0)\left(1 - \eta T^{3/2}\right) \tag{1}$$

where η is the temperature coefficient of spin-polarization, while the STMD resistance in a perpendicular magnetic state $R_\perp = {\rm RA}/(\pi r^2)$ is determined by

$$R_\perp(T) = R_\perp(0)\,(1 - \chi T) \tag{2}$$

where χ is the temperature coefficient of resistance [22], [23] and RA is the temperature-dependent resistance-area product of the MTJ. Conventional parallel (R_P) and antiparallel (R_{AP}) resistances of an MTJ are connected to $R_\perp$ and P by $R_P = R_\perp/(1+P^2)$, $R_{AP} = R_\perp/(1-P^2)$, whereas conventional TMR ratio can be found as $TMR = (R_{AP} - R_P)/R_P = 2P^2/(1-P^2)$. We also used the following expression for the temperature dependence of the static magnetization $M_s(T)$:

$$M_s(T) = M_s(0)\left(1 - \frac{T}{T_C}\right)^\tau \tag{3}$$

where T_C is the Curie temperature and τ is dimensionless parameter, typically selected within the range from 0.1 and up to 0.5 [24].

In the scope of our model the parameters $\varepsilon(T)$, $SNR(T)$, and $P_{\min}[50\ \Omega](T)$ of the STMD at the resonance frequency $f_s = f_0$ can be written as [17], [21]

$$\varepsilon(T) = \left(\frac{\gamma\hbar}{4e}\right)\frac{P^3(T)}{M_s(T)V\Gamma(T)} \times \frac{\sin^2\beta_0}{\left[1+P^2(T)\cos\beta_0\right]^2} \tag{4}$$

$$SNR(T) = \frac{P_{\rm RF}}{P_{\rm JN}(T)}\sqrt{\frac{P_{\rm MN}(T)}{P_{\rm MN}(T)+P_{\rm RF}}} \tag{5}$$

$$P_{\min}[50\ \Omega](T) = \frac{1}{4}\frac{\left[R(T)+Z_{\rm L}\right]^2}{R(T)Z_{\rm L}}P_{\rm JN}(T) \times \left[\frac{P_{\rm JN}(T)}{2P_{\rm MN}(T)} + \sqrt{\frac{P_{\rm JN}^2(T)}{4P_{\rm MN}^2(T)}+1}\right]. \tag{6}$$

Here $\hbar$ is the reduced Planck constant, e is the modulus of the electron charge, $V = \pi r^2 d$ is the volume of the FL (r is its radius and d is its thickness), β_0 is the angle between the static magnetization in the FL and PL of the STMD

$$R(T) = \frac{R_\perp(T)}{1+P^2(T)\cos\beta_0} \tag{7}$$

is the STMD resistance, $Z_{\rm L} = 50\ \Omega$ is the impedance of the detector's input transmission line. The expressions for noise powers $P_{\rm JN}$ and $P_{\rm MN}$ have the form [21]

$$P_{\rm JN}(T) = \frac{\sqrt{4k_BTR(T)\Delta f}}{\varepsilon(T)} \tag{8}$$

$$P_{\rm MN}(T) = \frac{\gamma\hbar}{2e}\frac{B_0}{P(T)\varepsilon(T)} \tag{9}$$

where k_B is the Boltzmann constant and Δf is the frequency bandwidth of measurement (we assume $\Delta f \ll \Gamma/2\pi$).

III. Results and Discussion

In our calculations we used the following typical parameters of the Permalloy ($Ni_{80}Fe_{20}$) FL in the MTJ nanopillar having composition $Co/Al_2O_3/Ni_{80}Fe_{20}$ taken at room temperature $T = 300$ K (see e.g., [17], [21]–[23]): radius of the nanopillar $r = 50$ nm, thickness of the FL $d = 1$ nm, spin-polarization efficiency $P(300\ {\rm K}) = 0.7$, temperature coefficient of spin polarization $\eta = 4\cdot10^{-5}\ {\rm K}^{-3/2}$ [23], angle between equilibrium magnetization of the FL and PL $\beta_0 = \pi/2$, temperature coefficient of resistance $\chi = \chi_0 = 7.65\cdot10^{-4}$ K [23], equilibrium resistance of an STMD $R(300\ {\rm K}) = 1\ {\rm k}\Omega$ (corresponding to ${\rm RA}(300\ {\rm K}) = 7.85\ \Omega\ \mu{\rm m}^2$), Gilbert damping constant $\alpha = 0.01$, saturation magnetization of the FL $\mu_0 M_s(300\ {\rm K}) = 0.8$ T, the Curie temperature $T_C = 822$ K [25], power coefficient $\tau = 0.4$, in-plane bias DC magnetic field $B_0 = 38$ mT (giving $f_0 = 5$ GHz, $\Gamma/2\pi = 122$ MHz at $T = 300$ K). For these parameters (4) gives the resonance STMD sensitivity in the passive regime $\varepsilon(300\ {\rm K}) \approx 2500$ V/W, which is comparable to the sensitivity of Schottky diodes [12], [20].

We also assume that the power of external microwave signal $P_{\rm RF} = 1\ \mu$ W and the measurement bandwidth $\Delta f = 1$ MHz. According to (8), (9) it gives the following estimations for the noise powers: $P_{\rm JN} = 1.57$ nW and $P_{\rm MN} = 1.22$ nW at $T = 300$ K.

The dependences of $\varepsilon(T)$ and $SNR(T)$ on temperature T are shown in Fig. 1 and temperature dependence of $P_{\min}[50\ \Omega](T)$ is shown in Fig. 2.

One can see from Fig. 1 that, for relatively high temperatures ($T > 50$ K), the sensitivity $\varepsilon(T)$ monotonically decreases with the increase of temperature T, mainly due to the temperature dependence of the spin polarization efficiency $P(T)$—see (1), (4). At low temperatures ($T < 50$ K), the sensitivity $\varepsilon(T)$ slightly increases with T. This behavior is explained by the reduction of static magnetization $M_s(T)$, which, in this temperature interval, has stronger temperature dependence than $P(T)$. The maximum of the curve $\varepsilon(T)$ corresponds to the temperature T_ε at which the factor $P^3(T)/[M_s(T)\Gamma(T)]$ reaches its maximum value. Note, that in the case of $\beta_0 \neq \pi/2$ the reduction of $\varepsilon(T)$ with a decrease of the temperature T in the range $T < T_\varepsilon$ may become

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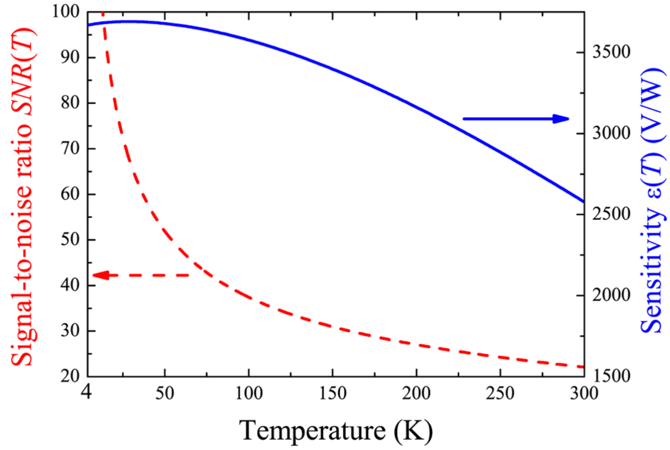

Fig. 1. Dependences of resonance volt-watt sensitivity $\varepsilon(T)$ (solid line) and signal-to-noise ratio $SNR(T)$ (dashed line) on temperature T for the STMD with typical parameters (see Section III for details).

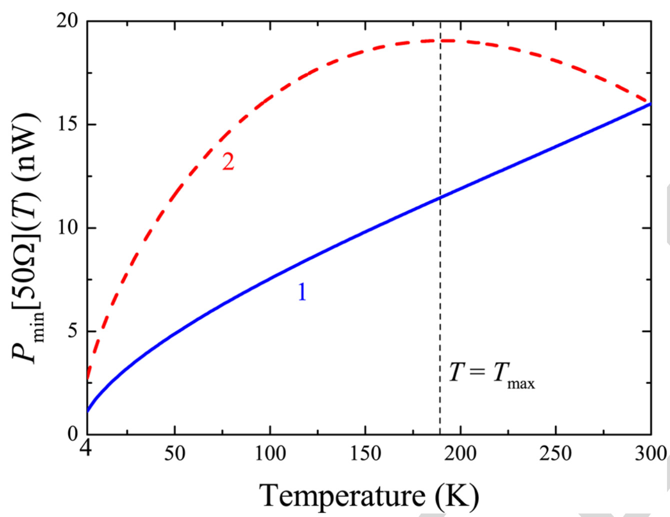

Fig. 2. Temperature dependences of minimal detectable microwave power $P_{\min}[50\ \Omega](T)$ for the STMD with temperature coefficient of resistance $\chi = \chi_0$ (curve 1, solid line) and $\chi = 2.5\chi_0$ (curve 2, dashed line). All other parameters are the same as for Fig. 1 (see also Section III for details).

more pronounced. It means, that cooling the STMD to very low temperatures (of the order of 4 K) may have an adverse effect in the form of reduction of its sensitivity.

In contrast to the temperature dependence of $\varepsilon(T)$, the signal-to-noise ratio $SNR(T)$ monotonically decreases with the increase of temperature (see dashed line in Fig. 1). This dependence is defined, mainly, by the rapid increase ($\propto \sqrt{T}$) of the Jonhson-Nyquist noise power $P_{\rm JN}(T)$ with the temperature.

The temperature dependence of the minimal detectable microwave power $P_{\min}[50\ \Omega](T)$, shown in Fig. 2, is more complicated than the temperature dependencies $\varepsilon(T)$ and $SNR(T)$. For some values of detector's parameters the curve $P_{\min}[50\ \Omega](T)$ may have a clear maximum at certain temperature $T_{\max}$. For instance, this situation is realized for an STMD with high enough temperature coefficient of resistance χ (see curve 2 in Fig. 2).

The temperature dependence of $P_{\min}[50\ \Omega](T)$ is determined by two main factors: by the temperature dependence of the "intrinsic" minimal detectable power $P_{\min}(T)$ (without taking into account the impedance mismatch effect), which is determined from the equation $SNR(T) = 1$, and the temperature dependence of the impedance mismatch coefficient $\rho(T) = [R(T) + Z_{\rm L}]^2/[R(T)Z_{\rm L}]$ for the detector and the transmission line. Since $SNR(T)$ monotonically decreases with the increase of the temperature, the "intrinsic" power $P_{\min}(T)$ monotonically increases with T. For small temperature coefficient of resistance χ, the temperature dependence of $P_{\min}[50\ \Omega](T)$ is determined mainly by the "intrinsic" minimum power $P_{\min}$ and has a monotonic shape (see curve 1 in Fig. 2).

If the temperature coefficient of resistance χ is large, the temperature dependence of the mismatch $\rho(T)$ may become stronger than the dependence $P_{\min}(T)$. For typical STMD parameters, $\rho(T)$ decreases with the increase of temperature (STMD resistance decreases and the mismatch with the transmission line reduces). As a result, the minimum detectable power $P_{\min}[50\ \Omega](T)$ decreases at high temperatures and reaches maximum value at a certain finite temperature $T_{\max}$ (see curve 2 in Fig. 2). In this regime, cooling of a STMD improves its characteristics only in the low-temperature region $T < T_{\max}$.

IV. Conclusion

In conclusion, we have demonstrated that the volt-watt sensitivity $\varepsilon(T)$ and minimum detectable microwave power $P_{\min}[50\ \Omega](T)$ of a resonance-type STMD do not always increase with an increase of the temperature, while the temperature dependence of the signal-to-noise ratio of a STMD $SNR(T)$ is always monotonic. The non-monotonic behavior of the sensitivity $\varepsilon(T)$ is determined by the interplay of temperature dependencies of the static magnetization $M_s(T)$ and spin polarization $P(T)$. The temperature dependence of the minimum detectable power $P_{\min}[50\ \Omega](T)$ is defined by two competing factors—noise power $P_{\rm JN}(T)$ and impedance mismatch $\rho(T)$,—and can have a maximum at temperatures $T_{\max} \sim 200$K. The developed formalism can be used for the optimization of practical parameters of a STMD in a wide range of temperatures.

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[1]Taras Shevchenko National University of Kyiv, Kyiv 01601, Ukraine
[2]U.S. Army TARDEC, Warren, MI 48397 USA
[3]Oakland University, Rochester, MI 48309 USA

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Recent experimental results [12], [13], [18], [19] have demonstrated that the volt-watt sensitivity $\varepsilon = U_{\rm DC}/P_{\rm RF}$ of a STMD based on the spin-torque diode effect can exceed that of passive semiconductor Schottky-diode microwave detectors. This makes STMDs very interesting for practical applications in microwave electronics.

The operation and the performance of all types of microwave detectors are limited by noise (in particular, by the low-frequency Johnson-Nyquist noise in the case of unbiased Schottky diodes [20]), and, therefore, depend on the temperature. In the case of magnetic STMDs the temperature dependence of detector's characteristics may be non-trivial, since many STMD parameters besides the noise level (e.g., saturation magntetization and spin-polarization efficiency) also change with the temperature.

In this work we analyze the influence of temperature T on the performance of a passive STMD, namely, we studied the temperature dependences of STMD sensitivity $\varepsilon_{\rm res}$ [17], signal-to-noise ratio SNR, and minimum detectable microwave power $P_{\rm min}[50\ \Omega]$ (for a detector connected to a standard 50 Ω transmission line) [21]. We believe that the developed formalism can be used for the optimization of the practical parameters of an STMD in a wide range of temperatures.

II. Theoretical Model

In this section we present a theoretical analysis of the performance of a passive STMD (no DC bias current) using the STMD model developed in [16], [21].

We consider a "planar" STMD based on a isotropic circular nanopillar of the radius r, in which both the free magnetic layer (FL) and the pinned magnetic layer (PL) are magnetized in-plane. In this case, the MTJ eigen-frequency is $f_0 = (\gamma/2\pi)\sqrt{B_0(B_0+\mu_0 M_s)}$ and the damping rate has the form $\Gamma = \alpha\gamma(B_0 + \mu_0 M_s/2)$, where $\gamma \approx 2\pi \cdot 28$ GHz/T is the modulus of the gyromagnetic ratio, M_s is the saturation magnetization of the FL of MTJ, α is the Gilbert damping constant, μ_0 is the vacuum permeability and B_0 is the in-plane bias DC magnetic field.

For simplicity we use the macrospin approximation for the FL of a STMD and also assume that the FL is isotropic over the entire temperature range. If this is not the case a more rigorous analysis should be performed [14]. Despite the obvious

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limitations of this model, we believe that it is qualitatively correct for isotropic magnetic materials (e.g., permalloy), at least for temperature range from 10 K to 300 K. If the materials with significant crystalline and strain-induced magnetic anisotropies (e.g., Co) are used for the MTJ free layer (see e.g., [12]) a more sophisticated model for the magnetic state of the MTJ free layer at low temperatures might be needed.

We used the analytical theory of noise properties of a STMD developed in [21] and the expression for the resonance detector's sensitivity $\varepsilon_{\rm res}$ from [17]. We took into account two sources of thermal noise: low-frequency Johnson-Nyquist noise, which is characterized by a noise power $P_{\rm JN}$, and the magnetic noise with noise power $P_{\rm MN}$ (see [21] for details).

We assumed that the spin-polarization P of the bias current in the STMD depends on the temperature T as

$$P(T) = P(0)\left(1 - \eta T^{3/2}\right) \tag{1}$$

where η is the temperature coefficient of spin-polarization, while the STMD resistance in a perpendicular magnetic state $R_\perp = {\rm RA}/(\pi r^2)$ is determined by

$$R_\perp(T) = R_\perp(0)\,(1 - \chi T) \tag{2}$$

where χ is the temperature coefficient of resistance [22], [23] and RA is the temperature-dependent resistance-area product of the MTJ. Conventional parallel (R_P) and antiparallel (R_{AP}) resistances of an MTJ are connected to $R_\perp$ and P by $R_P = R_\perp/(1+P^2)$, $R_{AP} = R_\perp/(1-P^2)$, whereas conventional TMR ratio can be found as $TMR = (R_{AP} - R_P)/R_P = 2P^2/(1-P^2)$. We also used the following expression for the temperature dependence of the static magnetization $M_s(T)$:

$$M_s(T) = M_s(0)\left(1 - \frac{T}{T_C}\right)^\tau \tag{3}$$

where T_C is the Curie temperature and τ is dimensionless parameter, typically selected within the range from 0.1 and up to 0.5 [24].

In the scope of our model the parameters $\varepsilon(T)$, $SNR(T)$, and $P_{\rm min}[50\ \Omega](T)$ of the STMD at the resonance frequency $f_s = f_0$ can be written as [17], [21]

$$\varepsilon(T) = \left(\frac{\gamma\hbar}{4e}\right)\frac{P^3(T)}{M_s(T)V\Gamma(T)} \times \frac{\sin^2\beta_0}{\left[1 + P^2(T)\cos\beta_0\right]^2} \tag{4}$$

$$SNR(T) = \frac{P_{\rm RF}}{P_{\rm JN}(T)}\sqrt{\frac{P_{\rm MN}(T)}{P_{\rm MN}(T) + P_{\rm RF}}} \tag{5}$$

$$P_{\rm min}[50\ \Omega](T) = \frac{1}{4}\frac{\left[R(T) + Z_{\rm L}\right]^2}{R(T)Z_{\rm L}}P_{\rm JN}(T) \times \left[\frac{P_{\rm JN}(T)}{2P_{\rm MN}(T)} + \sqrt{\frac{P_{\rm JN}^2(T)}{4P_{\rm MN}^2(T)} + 1}\right]. \tag{6}$$

Here $\hbar$ is the reduced Planck constant, e is the modulus of the electron charge, $V = \pi r^2 d$ is the volume of the FL (r is its radius and d is its thickness), β_0 is the angle between the static magnetization in the FL and PL of the STMD

$$R(T) = \frac{R_\perp(T)}{1 + P^2(T)\cos\beta_0} \tag{7}$$

is the STMD resistance, $Z_{\rm L} = 50\ \Omega$ is the impedance of the detector's input transmission line. The expressions for noise powers $P_{\rm JN}$ and $P_{\rm MN}$ have the form [21]

$$P_{\rm JN}(T) = \frac{\sqrt{4k_B T R(T)\Delta f}}{\varepsilon(T)} \tag{8}$$

$$P_{\rm MN}(T) = \frac{\gamma\hbar}{2e}\frac{B_0}{P(T)\varepsilon(T)} \tag{9}$$

where k_B is the Boltzmann constant and Δf is the frequency bandwidth of measurement (we assume $\Delta f \ll \Gamma/2\pi$).

III. Results and Discussion

In our calculations we used the following typical parameters of the Permalloy ($\rm Ni_{80}Fe_{20}$) FL in the MTJ nanopillar having composition Co/$\rm Al_2O_3$/$\rm Ni_{80}Fe_{20}$ taken at room temperature $T = 300$ K (see e.g., [17], [21]–[23]): radius of the nanopillar $r = 50$ nm, thickness of the FL $d = 1$ nm, spin-polarization efficiency $P(300\ {\rm K}) = 0.7$, temperature coefficient of spin polarization $\eta = 4 \cdot 10^{-5}\ {\rm K}^{-3/2}$ [23], angle between equilibrium magnetization of the FL and PL $\beta_0 = \pi/2$, temperature coefficient of resistance $\chi = \chi_0 = 7.65 \cdot 10^{-4}$ K [23], equilibrium resistance of an STMD $R(300\ {\rm K}) = 1\ {\rm k}\Omega$ (corresponding to ${\rm RA}(300\ {\rm K}) = 7.85\ \Omega\ \mu{\rm m}^2$), Gilbert damping constant $\alpha = 0.01$, saturation magnetization of the FL $\mu_0 M_s(300\ {\rm K}) = 0.8$ T, the Curie temperature $T_C = 822$ K [25], power coefficient $\tau = 0.4$, in-plane bias DC magnetic field $B_0 = 38$ mT (giving $f_0 = 5$ GHz, $\Gamma/2\pi = 122$ MHz at $T = 300$ K). For these parameters (4) gives the resonance STMD sensitivity in the passive regime $\varepsilon(300\ {\rm K}) \approx 2500$ V/W, which is comparable to the sensitivity of Schottky diodes [12], [20].

We also assume that the power of external microwave signal $P_{\rm RF} = 1\ \mu$ W and the measurement bandwidth $\Delta f = 1$ MHz. According to (8), (9) it gives the following estimations for the noise powers: $P_{\rm JN} = 1.57$ nW and $P_{\rm MN} = 1.22$ nW at $T = 300$ K.

The dependences of $\varepsilon(T)$ and $SNR(T)$ on temperature T are shown in Fig. 1 and temperature dependence of $P_{\rm min}[50\ \Omega](T)$ is shown in Fig. 2.

One can see from Fig. 1 that, for relatively high temperatures ($T > 50$ K), the sensitivity $\varepsilon(T)$ monotonically decreases with the increase of temperature T, mainly due to the temperature dependence of the spin polarization efficiency $P(T)$—see (1), (4). At low temperatures ($T < 50$ K), the sensitivity $\varepsilon(T)$ slightly increases with T. This behavior is explained by the reduction of static magnetization $M_s(T)$, which, in this temperature interval, has stronger temperature dependence than $P(T)$. The maximum of the curve $\varepsilon(T)$ corresponds to the temperature T_ε at which the factor $P^3(T)/[M_s(T)\Gamma(T)]$ reaches its maximum value. Note, that in the case of $\beta_0 \neq \pi/2$ the reduction of $\varepsilon(T)$ with a decrease of the temperature T in the range $T < T_\varepsilon$ may become

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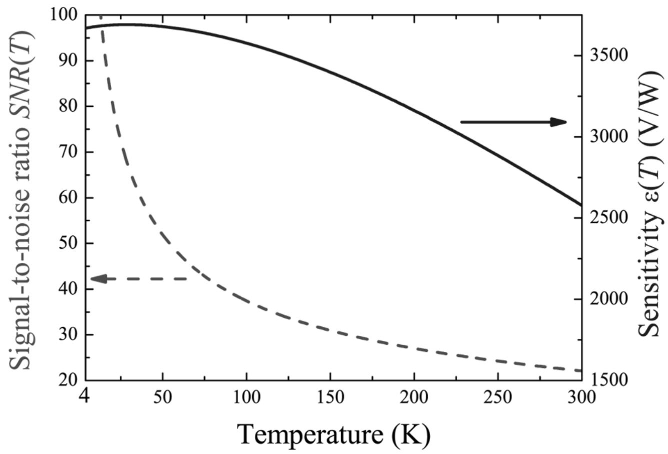

Fig. 1. Dependences of resonance volt-watt sensitivity $\varepsilon(T)$ (solid line) and signal-to-noise ratio $SNR(T)$ (dashed line) on temperature T for the STMD with typical parameters (see Section III for details).

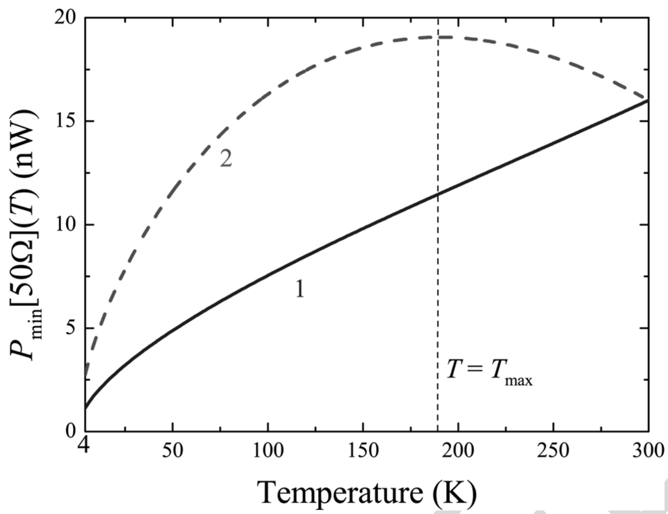

Fig. 2. Temperature dependences of minimal detectable microwave power $P_{\min}[50\ \Omega](T)$ for the STMD with temperature coefficient of resistance $\chi = \chi_0$ (curve 1, solid line) and $\chi = 2.5\chi_0$ (curve 2, dashed line). All other parameters are the same as for Fig. 1 (see also Section III for details).

more pronounced. It means, that cooling the STMD to very low temperatures (of the order of 4 K) may have an adverse effect in the form of reduction of its sensitivity.

In contrast to the temperature dependence of $\varepsilon(T)$, the signal-to-noise ratio $SNR(T)$ monotonically decreases with the increase of temperature (see dashed line in Fig. 1). This dependence is defined, mainly, by the rapid increase ($\propto \sqrt{T}$) of the Jonhson-Nyquist noise power $P_{\mathrm{JN}}(T)$ with the temperature.

The temperature dependence of the minimal detectable microwave power $P_{\min}[50\ \Omega](T)$, shown in Fig. 2, is more complicated than the temperature dependencies $\varepsilon(T)$ and $SNR(T)$. For some values of detector's parameters the curve $P_{\min}[50\ \Omega](T)$ may have a clear maximum at certain temperature $T_{\max}$. For instance, this situation is realized for an STMD with high enough temperature coefficient of resistance χ (see curve 2 in Fig. 2).

The temperature dependence of $P_{\min}[50\ \Omega](T)$ is determined by two main factors: by the temperature dependence of the "intrinsic" minimal detectable power $P_{\min}(T)$ (without taking into account the impedance mismatch effect), which is determined from the equation $SNR(T) = 1$, and the temperature dependence of the impedance mismatch coefficient $\rho(T) = [R(T) + Z_{\mathrm{L}}]^2/[R(T)Z_{\mathrm{L}}]$ for the detector and the transmission line. Since $SNR(T)$ monotonically decreases with the increase of the temperature, the "intrinsic" power $P_{\min}(T)$ monotonically increases with T. For small temperature coefficient of resistance χ, the temperature dependence of $P_{\min}[50\ \Omega](T)$ is determined mainly by the "intrinsic" minimum power $P_{\min}$ and has a monotonic shape (see curve 1 in Fig. 2).

If the temperature coefficient of resistance χ is large, the temperature dependence of the mismatch $\rho(T)$ may become stronger than the dependence $P_{\min}(T)$. For typical STMD parameters, $\rho(T)$ decreases with the increase of temperature (STMD resistance decreases and the mismatch with the transmission line reduces). As a result, the minimum detectable power $P_{\min}[50\ \Omega](T)$ decreases at high temperatures and reaches maximum value at a certain finite temperature $T_{\max}$ (see curve 2 in Fig. 2). In this regime, cooling of a STMD improves its characteristics only in the low-temperature region $T < T_{\max}$.

IV. Conclusion

In conclusion, we have demonstrated that the volt-watt sensitivity $\varepsilon(T)$ and minimum detectable microwave power $P_{\min}[50\ \Omega](T)$ of a resonance-type STMD do not always increase with an increase of the temperature, while the temperature dependence of the signal-to-noise ratio of a STMD $SNR(T)$ is always monotonic. The non-monotonic behavior of the sensitivity $\varepsilon(T)$ is determined by the interplay of temperature dependencies of the static magnetization $M_s(T)$ and spin polarization $P(T)$. The temperature dependence of the minimum detectable power $P_{\min}[50\ \Omega](T)$ is defined by two competing factors—noise power $P_{\mathrm{JN}}(T)$ and impedance mismatch $\rho(T)$,—and can have a maximum at temperatures $T_{\max} \sim 200$K. The developed formalism can be used for the optimization of practical parameters of a STMD in a wide range of temperatures.

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